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CROSS-CORRELATION ANALYSIS OF *WMAP* AND *EGRET* IN WAVELET SPACE

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ABSTRACT

We cross correlate the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) first year data and the diffuse gamma-ray intensity maps from the *Energetic Gamma Ray Experiment Telescope* (*EGRET*) using spherical wavelet approaches. Correlations at 99.7% significance level have been detected, at scales around 15° in the *WMAP* foreground cleaned W-band and Q-band maps, based on data from regions that are outside the most conservative *WMAP* foreground mask; no significant correlation is found with the Tegmark cleaned map. The detected correlation is most likely of Galactic origin, and thus can help us probing the origins of possible Galactic foreground residuals and ultimately removing them from measured microwave sky maps.

Subject headings: cosmic microwave background — cosmic rays — diffuse radiation — methods: data analysis

1. INTRODUCTION

The study of the anisotropies of the cosmic microwave background (CMB) is a powerful tool in cosmology. Results from the Wilkinson Microwave Anisotropy Probe (*WMAP*) provide us with the angular power spectrum and its cosmological implications (Bennett *et al.* 2003a; Spergel *et al.* 2003; Page *et al.* 2003). However unwanted signals due to foregrounds would contaminate any intrinsic signals, most importantly on large angular scales (Tegmark & Efstathiou 1996; de Oliveira-Costa *et al.* 2003).

The *WMAP* team chose the CMB-dominated bands (two Q-band maps at 40.7 GHz, two V-band maps at 60.8 GHz and four W-band maps at 93.5 GHz) and combined them to give a signal-to-noise ratio enhanced map. Despite that the maps at selected frequencies are dominated by CMB, Galactic foregrounds as well as extragalactic point sources all contribute significantly to the map, where the *WMAP* team performed a foreground template fit (thermal dust from Finkbeiner *et al.* 1999; free-free from Finkbeiner 2003 and Schlegel *et al.* 1998; synchrotron from Haslam *et al.* 1982) to avoid the Galactic emissions and separated them from the underlying CMB signal according to the frequency-dependence property of foregrounds (Bennett *et al.* 2003b). Since the foreground fluctuations depend on the multipole moment l as well (Bouchet *et al.* 1995), l-dependent statistical weights have been applied in Tegmark *et al.* (2003) where an independent foreground analysis was made. Several works of *WMAP* non-Gaussianity detection found residuals or the systematic effect correction as the sources (Chiang *et al.* 2003; Chiang & Naselsky 2004; Naselsky, Doroshkevich & Verkhodanov 2003, 2004; Eriksen *et al.* 2004; Hansen *et al.* 2004; Liu & Zhang 2005).

Wibig and Wolfendale (2005) have shown evidence that the Tegmark cleaned map contains residual foregrounds possibly induced by cosmic rays, where the Energetic Gamma Ray Experiment Telescope (*EGRET*) diffuse gamma-ray intensity map (Hunter *et al.* 1997) was adopted as the Galactic tracer. Diffuse Galactic gamma-ray emission is supposedly produced in interactions of Galactic cosmic rays with the interstellar gas and radiation field, and thus provides us with an indirect measurement of cosmic rays in various locations in the Galaxy [5] In this paper we cross-correlate the *WMAP* first-year data and the *EGRET* maps, which are based on more data and more complete point-source subtraction (Cillis & Hartman 2005), in wavelet space to probe the origins of potential residual foregrounds with characteristic scales. Both the *WMAP* combined foreground cleaned maps (Bennett *et al.* 2003b) and the Tegmark cleaned map (Tegmark *et al.* 2003) have been used.

2. CROSS-CORRELATION IN WAVELET SPACE

A measure of the correspondence of two data sets on the sphere is the angular cross-correlation function $CCF(\theta)$, which represents how the two measures of the sky separated by an angle θ are correlated. Previous works have performed the cross correlation of the CMB data and the nearby galaxy density tracers in search for the Integrated Sachs-Wolfe effect (ISW) (Boughn & Crittenden 2002, 2004; Nolta *et al.* 2004; Fosalba & Gaztañaga 2004; Fosalba *et al.* 2004; Afshordi *et al.* 2004; Vielva *et al.* 2004b). As being performed in Vielva *et al.* (2004b), cross-correlation studies can also be made in wavelet space.

Wavelet approach is very useful for detecting signals with a characteristic scale that a most optimal detection can be made by filtering the data at a given scale, thus structures at that scale are amplified. It has been adopted in the CMB-related analysis for non-Gaussianity studies (Hobson *et al.* 1999; Barreiro *et al.* 2000; Aghanim *et al.* 2003; Cayón *et al.* 2001, 2003; Martínez-

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[5] See Bertsch *et al.* 1993 and Hunter *et al.* 1997 for three-dimensional modeling.

González *et al.* 2002; Mukherjee & Wang, 2004; Vielva *et al.* 2004a; McEwen *et al.* 2004; Liu & Zhang 2005). In wavelet space, the cross-correlation covariance at a given scale a is defined as (Vielva *et al.* 2004b):

$$Cov_{_{W-E}}(a) = \frac{1}{N_a}\sum_{\vec{p}} \omega_{_{CMB}}(a,\vec{p})\omega_{_{EGRET}}(a,\vec{p}), \qquad (1)$$

where $\omega_{_{CMB}}(a,\vec{p})$ and $\omega_{_{EGRET}}(a,\vec{p})$ are the wavelet coefficients of the *WMAP* and *EGRET* data at position $\vec{p}$ on the sky map, and the sum $\sum_{\vec{p}}$ is extended over all the pixels (N_a) that are not masked by the Galactic mask "Kp0". Equation (1) gives the auto-correlation covariance (ACC) when the two data sets are the same. To make the analysis more robust and less sensitive to any discrepancies between CMB data and simulations, we use the dimensionless and normalized cross-correlation coefficient $C_{_{W-E}}(\theta)$ as the test statistics, which is given by $C_{_{W-E}}(\theta) = Cov_{_{W-E}}(\theta)/(\sigma_{_W}\sigma_{_E})$, where $\sigma^2_{_W} = ACC_{_W}$ and $\sigma^2_{_E} = ACC_{_E}$ are the *WMAP* and *EGRET* auto-correlation covariances respectively.

The wavelet coefficients are obtained by convolving the map with a certain spherical wavelet basis at a given scale:

$$\omega_{_D}(a,\vec{p}) = \int d\Omega'\, D(\vec{p}+\vec{p'})\Psi_S(\theta',a), \qquad (2)$$

where $\Psi_S(\theta',a)$ is the spherical wavelet basis and $D(\vec{p}+\vec{p'})$ is the data set to be analyzed. The spherical wavelet can be obtained from the Euclidean Wavelet counterpart following the stereographic projection suggested by Antoine & Vanderheynst (1998). Martínez-González *et al.* (2002) has described the projection for the Spherical Mexican Hat Wavelet (SMHW) as well as its properties, whereas the Spherical Morlet Wavelet (SMW) has been applied for non-Gaussianity detection in the *WMAP* data (McEwen *et al.* 2004, Liu & Zhang 2005). In this correlation study we have adopted both wavelets, of which the SMW seems to be more sensitive than the SMHW. We only present results from the SMW analysis here, even though similar correlations are also found when applying the SMHW.

The preprocessing pipelines for the *WMAP* CMB data and Monte Carlo simulations are the same as in Liu & Zhang (2005), whereas the gamma-ray intensity maps are degraded to the same resolution with the CMB data to be cross-correlated, all in equi-angular spherical grid pixalisation. The preprocessed maps are shown in Fig. 1. 10,000 simulations of the *WMAP* data have been applied, following the cosmological model given by the Table 1 of Spergel *et al.* (2003), to obtain the significance levels of any correlation detection. We obtain these levels in a robust way by taking into account the probability distribution of the wavelet cross-correlation coefficient at each scale. Although the map-making algorithm presented by Cillis and Hartman (2005) possibly produced some systematic effects in the *EGRET* data, these can be calibrated out by simulations.

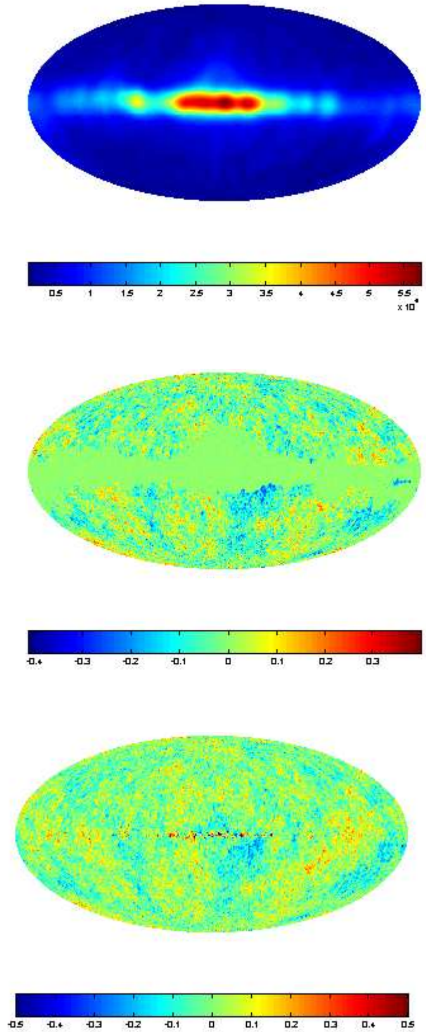

FIG. 1.— Preprocessed *EGRET* diffuse gamma-ray intensity map (> 1 GeV) (Cillis and Hartman 2005) and CMB anisotropy maps from the *WMAP* map (Bennett *et al.* 2003a) and the Tegmark cleaned map (Tegmark *et al.* 2003) to be analyzed in the cross-correlation study. Note that we have analyzed the EGRET diffuse gamma-ray intensity maps of different energies separately, i.e., 30−100 MeV, 100 − 300 MeV, 300 − 1000 MeV and > 1 GeV, where only the > 1 GeV map is shown here. All maps are plotted in Galactic coordinates with the Galactic center $(l, b) = (0, 0)$ in the middle and Galactic longitude l increasing to the left.

3. RESULTS

Cross correlation with the *EGRET* maps in wavelet space has been performed to both of the Q-V-W combined *WMAP* map and the Tegmark cleaned map to detect foreground residuals (here and throughout, all *WMAP* CMB maps used are foreground removed maps). Also we have performed the analysis to: (a) the *WMAP* map in each band separately, i.e. Q, V, and W; (b) systematic beam and noise maps from subtracting maps of the receivers at the same frequency; and (c) a foreground map almost free of CMB, which is made by subtracting the two receivers of Q band and the two receivers of V band from the four receivers of W band (Vielva *et al.* 2004a).

For every CMB related map, we have performed the analysis using *EGRET* maps in different energy ranges separately, i.e. 30 − 100 MeV, 100 − 300 MeV, 300 − 1000 MeV and > 1 GeV, and only the results from the > 1

GeV map are shown here because: (a) it has been stated by Cillis & Hartman (2005) that the > 1 GeV intensity map has the best statistical accuracy compared with others from lower energy ranges, where possible correlations can be smeared out by statistical uncertainty fluctuations; and (b) the analysis with different gamma-ray energy ranges stated above generally give similar correlations and the significance level seems to increase a little with the energy of the adopted gamma-ray data. Note this variance of correlation significance does not conflict with the power-law energy spectrum, since the cross-correlation coefficient is a normalized quantity.

The cross-correlation coefficients $C_{W-E}(\theta)$ are illustrated in Figs. 2(a) and 2(b), where the corresponding size θ on the sky can be obtained from equation (3) in Liu & Zhang (2005); we have analyzed scales from 1° to 90°, where we are only concerned about results at scales $> 4^\circ$ due to the angular resolution limit in the *EGRET* data. We have shown the ACCs (normalized by the map dispersion σ_0 in the real space) of the *WMAP* combined map, the Tegmark cleaned map, the foreground-component map and the diffuse gamma-ray intensity map in Fig. 2(c), which indicate that the general patterns of $C_{W-E}(\theta)$ in Figs. 2(a) and 2(b) are caused by the convolution of the gamma-ray data and the wavelets, not by systematical artifacts. Note at all the concerned scales the foreground map correlates more significantly with the *EGRET* map, consistent with the assumption that most of the foregrounds have been removed from the CMB maps. Results from analyzing the systematic beam and noise maps are not shown since their correlation coefficients are all consistent with zero values within statistical fluctuations.

For the *WMAP* CMB maps, correlations at 99.7% significant level are detected at scales from about 14° to 16°, in the W-band and Q-band maps; less significant correlations (96.8%) are found at larger scales, from about 43° to 48°, only in the W-band map. In sum, the W-band and Q-band maps exhibit more significant correlations compared with those from the V-band map, at all the concerned scales. This frequency dependence feature can be easily understood according to Fig. 10(a) in Bennett *et al.* (2003b), showing evidence that the detected correlations are caused by residual foreground signals. In order to test whether the detected signal has a Galactic origin, we have shown in Fig. 2(d) the cross-correlation coefficients as a function of the galactic latitude around $\theta = 15^\circ$. Note that the sum of the cross-correlation coefficients at all the latitudes in Fig. 2(d) corresponds to the $C_{W-E}(15^\circ)$ in Figs. 2(a). Here the oscillating pattern is given by the SMW, and we have tested that the outline profile is caused by the *EGRET* intensity maps. Tests at other scales also present similar profiles. The results show some consistency with the co-sec law for the Galactic components, and also present a north-south asymmetry where the correlation is stronger in the southern hemisphere.

Analysis of the Tegmark cleaned map does not show any significant correlation at all the concerned scales, as an evidence that it is "cleaner" than the *WMAP* combined map.

4. CONCLUSIONS AND DISCUSSIONS

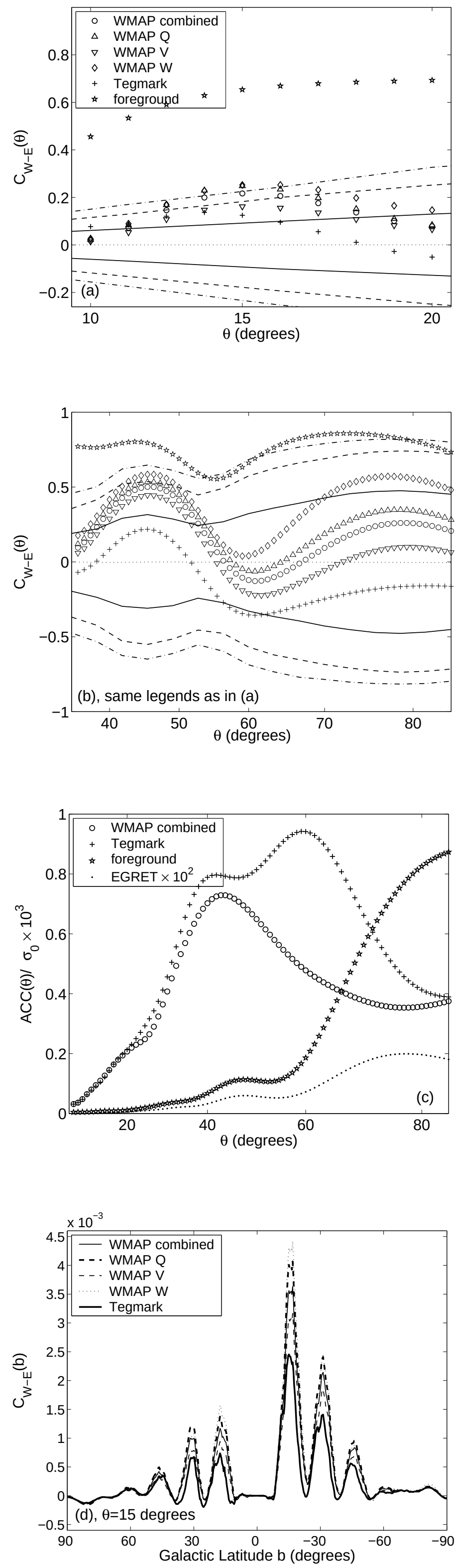

FIG. 2.— (a) and (b): cross-correlation coefficients $C_{W-E}(\theta)$ of the *WMAP* and *EGRET* data in wavelet space. The acceptance intervals at the 68% (solid), 95% (dashed) and 99% (dash-dotted) significance levels given by 10,000 Monte Carlo simulations are shown, respectively. The error bars are too small compared to the coefficient values and can be ignored in the figures; (c): normalized auto-correlation covariances, representing that the general patterns in (a) and (b) are caused by the convolution of the gamma-ray data and the wavelet basis, not by systematical artifacts; (d): cross-correlation coefficient as a function of the galactic latitude around $\theta = 15^\circ$, testing the Galactic origin of the detected correlations.

We have performed cross-correlation analysis of the *WMAP* first-year data with the *EGRET* diffuse gamma-ray intensity maps in wavelet space, finding correlations in the *WMAP* foreground cleaned maps, based on regions that are outside the most conservative *WMAP* foreground mask. Analysis of the *WMAP* W-band and Q-band maps exhibits correlation at 99.7% significant level at scales around 15° in the sky, and at scales around 45° less significant correlation (96.8%) is found only in the *WMAP* W-band map. The Tegmark cleaned map seems to be compatible with pure CMB simulations at all the concerned scales.

These cross-correlation signals are not caused by systematic beams nor noise because: (a) the analysis of the systematic beam and noise map show almost zero correlation results; and (b) the correlations are detected at the scales where noise and beam effects can be ignored (Tegmark *et al.* 2003). We thus conclude that these cross-correlation signals are most probably caused by foreground residuals because: (a) correlations from the Q and W bands are more significant than those from the V band, consistent with the frequency dependence nature of foreground; (b) the correlation coefficients from the CMB maps present similar patterns with those from the foreground map, whereas random simulations do not show correlations at the the detected level; (c) the Tegmark cleaned map, which has been commonly believed to be cleaner than the *WMAP* combined map in terms of the foreground removal, shows no significant correlation with the *EGRET* map in the analysis; and (d) the detected cross-correlation coefficient as a function of the galactic latitude appears to be consistent with the co-sec law as an evidence for the Galactic origin. It is possible that these foreground residuals may be induced by cosmic rays, since the Galactic diffuse gamma-ray emission is supposedly produced in interactions of cosmic rays with gas and ambient photon fields and thus can be an indicator of cosmic rays in various locations in the Galaxy.

The detected foreground residuals can be located in the coefficient map at a certain scale. It is therefore worthwhile to make correlation study with cosmic ray's spatial and spectral distributions in detail. Note that the diffuse gamma-ray emission has not been well understood that at energies > 1 GeV the observed intensity in inner Galaxy displays a GeV excess at a level of 60% compared with predictions (Hunter *et al.* 1997), which has been interpreted in several models (Strong *et al.* 2000; de Boer 2005). Further cross-correlation work must be done to fully understand the nature of foreground residuals and finally remove them from the CMB maps completely, in order to minimize the impacts of foreground residuals to the cosmological studies of CMB.

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REFERENCES

Afshordi, N., Loh, Y.-S., & Strauss, M. A. 2004, Phys. Rev. D, 69, 3524

Aghanim, N., Kunz, M., Castro, P. G., & Forni, O. 2003, A&A, 406, 797

Antoine, J.-P., & Vandergheynst, P. 1998, J. Math. Phys., 39, 3987

Barreiro, R. B., *et al.* 2000, MNRAS, 318, 475

Bennett, C. L., *et al.* 2003a, ApJS, 148, 1

Bennett, C. L., *et al.* 2003b, ApJS, 148, 97

Bertsch, D. L., *et al.* 1993, ApJ, 416, 587

Boughn, S. P., & Crittenden, R. G. 2002, Phys. Rev. Lett., 88, 21302

Boughn, S. P., & Crittenden, R. G. 2004, Nature, 427, 45

Bouchet, F., *et al.* 1995, Space Science Review, astro-ph/9410004

Cayón, L., *et al.* 2001, MNRAS, 326, 1243

Cayón, L., *et al.* 2003, MNRAS, 339, 1189

Chiang, L.-Y., Naselsky, P. D., Verkhodanov, O. V., & Way, M. J. 2003, ApJ, 590, L65

Chiang, L.-Y., & Naselsky, P. D. 2004, astro-ph/0407395

Cillis, A. N., & Hartman, R. C. 2005, ApJ, 621, 291

de Boer, W. 2005, New Astron.Rev., 49, 213

de Oliveira-Costa, A., *et al.* 2003, Phys. Rev. D, 68, 083003

Eriksen, H. K., Novikov, D. I., Lilie, P. B., Banday, A. J., Gorski, K. M. 2004, ApJ, 612, 64

Finkbeiner, D. P. 2003, ApJS, 146, 407

Finkbeiner, D. P., Davis, M., & Schlegel, D. J. 1999, ApJ, 524, 867

Fosalba, P., & Gaztañaga, E. 2004, MNRAS, 350, 37

Fosalba, P., Gaztañaga, E., & Castander, F. 2004, ApJ, 597, L89

Hansen, F. K., Cabella, P., Marinucci, D., & Vittorio, N. 2004, ApJ, 607, L67

Hartman, R. C., *et al.* 1999, ApJS, 123, 79

Haslam, C. G. T., Salter, C. J., Stoffel, H., & Wilson, W. E. 1982, A&AS, 47, 1

Hobson, M. P., *et al.* 1999, MNRAS, 309, 125

Hunter, S. D., *et al.* 1997, ApJ, 481, 205

Liu, X., & Zhang, S. N. 2005, ApJ, 633, 542

Martínez–González, E., *et al.* 2002, MNRAS, 336, 22

McEwen, J. D., *et al.* 2005, MNRAS, 359, 1583

Mukherjee, P., & Wang, Yun 2004, ApJ, 613, 51

Naselsky, P. D., Doroshkevich, A., & Verkhodanov, O. V. 2004, MNRAS, 349, 695

Naselsky, P. D., Doroshkevich, A., & Verkhodanov, O. V. 2003, ApJ, 599, L53

Nolta, M. R., *et al.* 2004, ApJ, 608, 10

Page, L., *et al.* 2003, ApJS, 148, 233

Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525

Spergel, D. N., *et al.* 2003, ApJS, 148, 175

Tegmark, M., & Efstathiou, G. 1996, MNRAS, 281, 1297

Tegmark, M., de Oliveira-Costa, A., & Hamilton, A. J. S. 2003, Phys. Rev. D, 68, 123523

Vielva, P., *et al.* 2004a, ApJ, 609, 22

Vielva, P., Martínez–González, E., & Tucci, M. 2004b, astro-ph/0408252

Wibig, T., & Wolfendale, A. W. 2005, MNRAS, 360, 236